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MINIREVIEW

A transnational and holistic breeding approach is needed for sustainable wheat production in the Baltic Sea region

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The Baltic Sea is one of the largest brackish water bodies in the world. Eutrophication is a major concern in the Baltic Sea due to the leakage of nutrients to the sea with agriculture being the primary source. Wheat (*Triticum aestivum* L.) is the most widely grown crop in the countries surrounding the Baltic Sea and thus promoting sustainable agriculture practices for wheat cultivation will have a major impact on reducing pollution in the Baltic Sea. This approach requires identifying and addressing key challenges for sustainable wheat production in the region. Implementing new technologies for climate-friendly breeding and digital farming across all surrounding countries should promote sustainable intensification of agriculture in the region. In this review, we highlight major challenges for wheat cultivation in the Baltic Sea region and discuss various solutions integrating transnational collaboration for pre-breeding and technology sharing to accelerate development of low input wheat cultivars with improved host plant resistance to pathogen and enhanced adaptability to the changing climate.

Abbreviations – DDT, dichlorodiphenyltrichloroethane; DK, Denmark; ECPGR, European Cooperative Programme for Plant Genetic Resources; EE, Estonia; FI, Finland; HCB, hexachlorobenzene; HCH, hexachlorocyclohexane; ICM, Integrated Crop Management; IWYP, International wheat yield potential; LT, Lithuania; N, Nitrogen; NPPN, Nordic plant phenotyping network; NUE, nitrogen use efficiency; PL, Poland; PPP, plant protection product; SE, Sweden; STB, Septoria tritici Blotch; WUE, water use efficiency.

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Introduction

The Baltic Sea is a brackish (low-salinity) water body and is considered to have obtained its present shape about 4000 years ago with over 250 rivers supplying freshwater (Ruskule et al. 2009). Marine pollution is a problem worldwide, but it is particularly acute in semi-closed seas. Baltic Sea is surrounded by land and is more at risk of pollution than open marine areas, due to industry and industrial agriculture, e.g. fertilizers and pesticides. One of the main concerns with the Baltic Sea is eutrophication – enrichment of water by nutrient compounds, causing an accelerated growth of algae and higher forms of plant life (Elmgren and Larsson 2001, Rönnberg and Bonsdorff 2004, Andersen et al. 2017). Eutrophication has increased in the Baltic Sea since 1950 and results in the reduction of dissolved oxygen thereby harming benthic organisms including fish and other aquatic life (Elmgren and Larsson 2001). Agriculture is one of the main sources for eutrophication due to nitrogen and phosphorous runoff from fields and emissions from fertilizers and manure (Elmgren and Larsson 2001, HELCOM 2011). The main pathways for leakage of nutrients into the sea are riverine inputs through the transportation of nutrients from rivers into the sea (Stalnacke et al. 1999).

Toxic pollution by pesticides and disinfectants is considered to be one of the main problems in the Baltic Sea which has a major impact on its biological diversity. Pesticides such as dichlorodiphenyltrichloroethane (DDT), triazine derivatives, hexachlorobenzene (HCB) or hexachlorocyclohexane (HCH) are toxic to aquatic organisms (Rheinheimer 1998, Reindl et al. 2015). These chemicals accumulate in food chains and can lead to various damages including reproduction impairment, and as a result they have been banned in the EU. In most countries, work is currently underway to minimize the use of pesticides in agriculture and to replace risky products with less toxic and easily degradable ones. After the prohibition of DDT, concentration of this organic pollutant in seals have fallen (Nyman et al. 2002). Concentrations of DDT in Baltic herring have now decreased and reach only 5% of what they were in 1970s (Sapota 2006) but the work toward a minimal or even a zero-use has to continue. How close to zero will depend, among other things, on selecting crops and cropping systems with less need for plant protection products.

According to the data supplied by European Crop Protection Association, the total amount of PPP used in the EU increased steadily in the 1990s, stabilizing in the late 1990s and then declined (EUROSTAT 2007). However, the total quantity of pesticides sold, expressed in active substances, increased between 2011 and 2014. During last decades, production techniques that use lower levels of PPPs have been increasingly applied, especially in organic farming. In parallel, new production techniques that have a lower impact on health and environment also have been introduced into the agronomic management of crops. In particular, Integrated Crop Management (ICM) is an approach that helps in reducing the dependency on PPPs. Increasing genetic diversity of cultivars will lead to considerable decrease in the pesticide use.

Based on the records available at the European statistical system – EUROSTAT (The European Commission 2017), the total area under cereal cultivation in the eight European countries (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland and Sweden) bordering the Baltic Sea was 19 million hectares (ha) in 2016, of which, wheat (*Triticum aestivum* L.) is grown on 8 million ha, making it the most important cereal in the region. The total area under wheat cultivation has grown steadily with an increase of 11.8% from 2007 to 2016 resulting in an average increase of 1.18% per annum. Wheat production in the region also increased by 12.6% between 2007 and 2016 with an average increase of 1.26% per annum and the production reached 49 million tons in 2016. This increase in production is attributed to the increase in acreage and improved wheat breeding and agronomic practices. Winter wheat has a larger share of the total wheat production in the Baltic Sea region countries. Winter wheat usually produces higher yields than spring wheat, and winter wheat production is expected to increase in the near future thus making it an important crop for the region. However, agricultural land is limited and thus sustained high grain yields of wheat and especially winter wheat should be produced with limited impact on the environment. This requires addressing the challenges hindering sustainable intensification of wheat production.

Key challenges for sustainable wheat production

The climate in the Baltic Sea countries varies from mild climate and high cultivation potential in Denmark, Germany, Poland and southern Sweden to more challenging climate in the northern parts of Finland and Sweden. In addition to the natural variability in climate, global warming has been observed during the past century. The warming trend for the entire globe was about 0.05°C per decade from 1861 to 2000, while the trend for the Baltic Sea basin has been upwards by 0.08 °C per decade (von Storch et al. 2015). The length of the frost-free season has increased in the Baltic Sea basin during this period consequently increasing the length of the growing season (Ingver et al. 2016). A general increase in annual precipitation is expected in certain areas, especially

Table 1. Wheat traits relevant for Baltic Sea costal countries and their phenotyping needs. DK, Denmark; EE, Estonia; FI, Finland; LT, Lithuania; PL, Poland; SE, Sweden.

Trait	Importance for the entire region	Country-specific relevance	Current phenotyping approaches	Current phenotyping limitations
1. Growth and development				
Early vigor	Low	All	Manual scoring	Time-consuming to score large number of plots
Root architecture	High	All	Soil scoring	Invasive, laborious
Heading time	High	All	Manual scoring	Time-consuming to score large number of plots
Lodging	High	All	Manual scoring	Time-consuming to score large number of plots
2. Physiology				
Nutrient use efficiency	High	All	Yield determination	Complex trait, difficult to phenotype
Water use efficiency	Medium	All	Yield determination	Complex trait, difficult to phenotype
3. Abiotic stress tolerance				
Winter hardiness	High	All	Manual scoring	Time-consuming to score large number of plots
Drought tolerance	Medium	All	Yield determination	Time-consuming to score large number of plots
4. Biotic stress resistance				
Septoria tritici blotch (*Zymoseptoria tritici*)	High	All	Manual scoring	Difficult to separate from other necrotrophes
Yellow rust (*Puccinia striiformis*)	High	DK, PL, SE	Manual scoring	Need nurseries to ensure good scoring
Powdery mildew (*Blumeria graminis*)	Medium	DK, FI, LT	Manual scoring	Early season, time-consuming to score large number of plots
Fusarium head blight (*Fusarium* spp.)	High	All	Manual scoring	Late season, toxin estimation is costly
Tan spot (*Pyrenophora tritici-repentis*)	Medium to High	DK, FI, LT	Manual scoring	Difficult to separate from other necrotrophes
Septoria glume blotch (*Stagonospora nodorum*)	Low	All	Manual scoring	Difficult to separate from other necrotrophes
Pink snow mold (*Microdochium nivale*)	Medium	All	Manual scoring	Can easily be confused with other pathogens

in the northern parts of the Baltic Sea basin, while in other parts, such as Denmark, the annual distribution of the precipitation is changing. These precipitation changes will affect the runoff into the Baltic Sea, with potential increases in mean annual river flow occurring from the northernmost regions together with decreases in the southernmost regions (HELCOM 2007). These challenges will affect the productivity of adapted wheat cultivars to this region (Table 1).

Nutrient use efficiency and farm management practices

Nitrogen (N) use efficiency (NUE) is defined as grain production per unit of N available in the soil (Moll et al. 1982). Wheat cultivars with high NUE are of particular importance to reduce the amount of N left in crop residue in field after harvest (Weih et al. 2011). The development of high-NUE cultivars over the last 30 years has been promising, partially spurred by national restrictions on the use of N-fertilizer (e.g. in Denmark), but further improvements are needed (van Grinsven et al. 2012). Another important factor for an increased NUE in wheat cultivation is the adjustment of N rate to the crop needs and the conditions in the field (Raun et al. 2002). High variation is found in N-optimum needs among years, fields and also among different parts in the same field. Several tools such as N-sensor (Yara International ASA, Oslo, Norway), ISARIA sensor system (Fritzmeier Umwelttechnik, Großhelfendorf, Germany), N-Tester (Yara International ASA, Oslo, Norway), Greenseeker (Trimble Agriculture, Sunnyvale, CA), Crop Circle (Holland Scientific, Lincoln, NE) and CropScan (Cropscan Inc., Rochester, NY) are available to assist farmers to optimize the N-level during the season with the variable N-rate technology. Use of such digital farming tools for N optimization makes it possible for the farmers to obtain high grain yields with low residual N in soil, thus leading to lower environmental impacts in terms of N leaching (Muñoz-Huerta et al. 2013). In some countries around the Baltic Sea, the new techniques are becoming popular. For example in Sweden, as of 2017, 220 Yara N-Sensors are used on 18% of total winter wheat acreage, while in some other countries, the N strategy does adapt to the circumstances. N applications, late in the growing season, are important for high grain yield, although such applications also influence the grain quality (Johansson et al. 2004, Johansson et al. 2013). Thus, breeding for cultivars with known physiological traits and the ability to obtain grain yield in a way that promotes the possibility of adjustments to N rate, late in the growing season, would be beneficial. It would then increase the possibility to use different tools to predict the actual N demand according to grain yield potential, quality requirements and soil N delivery.

Abiotic stresses

Abiotic stresses such as winter and frost damage, flooding and drought affect grain yield in the Baltic region, and thus, cultivars adapted to the local abiotic stresses are required (Ingver et al. 2010). The ability of winter wheat to acclimate (harden) during autumn to survive the extreme conditions in winter determines their northern limit of distribution. Overwintering plants must be tolerant to both abiotic (frost, ice or water cover, soil heaving, desiccation, plant starvation) and biotic [e.g. pink snow mold caused by *Microdochium nivale* (Fr.) Samuels & I.C. Hallett] stress factors. The winterkill factors vary from region to region and from year to year. Winter wheat acclimates at low non-freezing temperatures during autumn but above-zero temperatures in the winter cause de-acclimation and reduction in freezing tolerance and thus hampering overwintering. Typical problems with wheat overwintering are related to soil heaving and damaging roots, ice encasement causing anoxia, too deep snow cover increasing pathogen problems or lack of snow resulting in freezing of plants and de-acclimation (Bergjord et al. 2010, Jamalainen 1978). Extreme winter spells after thawing cause up to 90% yield loss in different regions, particularly in combination with low snow coverage (Armonienė et al. 2013, Vico et al. 2014, Gorash et al. 2017). In countries with colder weather conditions, major winterkill factors are low freezing temperatures (especially without snow cover) and pink snow mold. The exceptionally short growing season with long days, typically from 120 to 180 days, is limited by late spring and early autumn frosts as well as solar availability and uneven precipitation with dry spring and rainy autumn (Mukula and Rantanen 1987). Due to global warming, these thaw periods may become frequent and unpredictable in many locations of the Baltic Sea region (Vico et al. 2014). Hence, it is necessary to develop freezing tolerant winter wheat cultivars that can withstand freezing temperature following thaw periods in the region. Moreover, the presence of winter hardy wheat cultivars on agricultural fields reduces nutrient leaching to the ambient environment, thereby contributing to the efforts to tackle further eutrophication of the Baltic Sea.

In coming decades, drought is expected to expand globally due to the effects of increased evaporation and reduced rainfall or changes in the spatial and temporal distribution of rainfall (Dai 2012). Late spring and early summer drought (April, May and June) is observed regularly in the region and is one of the main abiotic stresses decreasing grain yield dramatically (Mukula and Rantanen 1987, Doroszewski et al. 2012, Tao et al. 2015). The likelihood of late spring drought periods is also increasing in Sweden and Denmark in combination with more precipitations in the early spring and late summer (The Swedish Commission on Climate and Vulnerability 2007, Arheimer and Lindström 2015). Late spring drought is particularly damaging for spring wheat because, unlike winter wheat, roots in spring wheat are not well developed at that time thus restricting access to water from the deeper soil layers. In some regions of Poland, up to 30% yield loss was observed in extreme drought (Doroszewski et al. 2012). Hence, breeding for both drought tolerance and high-yielding nutritionally reach cultivars is necessary for spring wheat. Water use efficiency (WUE) is the measure of the capacity of plants to utilize the available water for producing biomass and grain yield (Stanhill 1986). WUE increases the productivity of plants under water limited conditions (Passioura 2006, Reynolds and Tuberosa 2008). WUE was shown to be higher in spikes than leaves and contributes with up to 40% more carbon fixation under moisture stress (Evans et al. 1972). Thus, WUE has important applications in breeding. In Poland, there are many areas with nutrient poor soils where high yields cannot be obtained (Fotyma 2000). Thus, field trials on such soils are necessary to select for breeding lines well adapted to poor soils. Screening of wheat genotypes in field trials, high-throughput phenotyping facilities, freezing chambers and genetic tools (mutagenesis or linkage and association mapping) are required to identify genotypes with higher abiotic stress tolerance. New abiotic stress tolerant varieties can also be developed through approaches that involve mutagenesis.

Biotic stresses

Another factor affecting the grain yield in cereals is pathogens causing diseases of economic importance. Several wheat diseases are common in the Baltic Sea region including Septoria tritici Blotch (STB) (*Zymoseptoria tritici* Desm.), tan spot [*Pyrenophora tritici-repentis*

(Died.) Drechs.], Septoria glume blotch (*Stagonospora nodorum* Berk.), leaf or brown rust (*Puccinia triticina* Eriks.), yellow or stripe rust (*Puccinia striiformis* Westend f. sp. *tritici* Erikss.), Fusarium head blight (*Fusarium* spp.), powdery mildew [*Blumeria graminis* (DC.) Speer f. sp. *tritici* Em. Marchal], and pink snow mold [*M. nivale* (Fr.) Samuels & I.C. Hallett]. Depending on the season and the location, the impact of these diseases on grain yield is highly variable (Jørgensen et al. 2014). Major differences in grain yield losses in the region were observed depending on the resistance of cultivars to diseases and STB was found to be a major cause for yield loss in untreated trials (Jørgensen et al. 2014). In recent years, new races of yellow rust were detected in Northern Europe increasing the risk of new disease epidemics in the region (Hovmøller et al. 2016). In Europe, stem rust (*Puccinia graminis* f. sp. *tritici* Eriks. & E. Henn) was detected after several decades on a single plant in the United Kingdom in 2013 (Lewis et al. 2018), and bigger sporadic outbreaks in central Germany in 2013 (Olivera Firpo et al. 2017), Sicily in 2016 (Bhattacharya 2017) and in central Sweden in 2017 (Berlin 2017). Thus, major diseases, invasion of exotic pathogen races and new emerging diseases are a major threat to grain yield stability.

Another key challenge is knowing the appropriate timing and dosage of fungicides for a given situation (Jørgensen et al. 2017). Fungicides are used in a varying extent in different countries with applications varying from 1 to 3 treatments per season. Without fungicide application, grain yields of up to 7 or 9 $\mathrm{t\,ha^{-1}}$ are achievable in winter wheat but fungicide application can increase the grain yield by up to 3 $\mathrm{t\,ha^{-1}}$ depending on the year and cultivar (Jørgensen et al. 2014). Fungicide application in most cases could increase grain quality like thousand grain weight and specific weight/hectoliter weight. However, fungicides are generally seen as a cost-effective tool for farmers (Wiik and Rosenqvist 2010).

Despite many attempts to improve thresholds for applying fungicides, major uncertainties still exist and also major barriers in adopting decision support systems within the farming community have been recognized (Jørgensen et al. 2008). A recent survey addressing fungicide resistance confirmed widespread resistance in the *Z. tritici* population to QoI fungicides and also an increasing buildup of mutations related to azoles (Heick et al. 2017). The general desire to be less dependent on fungicides and the increasing problems with fungicide resistance, collectively calls for the more widespread use of integrated pest management measures such as growing cultivars with good resistance to major pathogens and pests. In general, cultivars are developed with resistance to some of the major diseases, yet fungicide application is still a necessity on many occasions to minimize losses in grain yields due to prevalence of mutliple diseases in the region. The necessity is to develop reliable tools for accurate disease forecasting that could help wheat growers in choosing right product and application timing. In addition, high yielding cultivars are required with improved resistance to various pathogens and pests in the region.

Optimizing phenotyping for disease resistance can be done more effectively by including both field and greenhouse methods. Some localities have climatic condition more supportive for screening for specific pathogens than others (e.g. snow mold in northern countries). For other diseases, artificial inoculation with relevant pathogens representative for the Baltic sea region can be organized in either field trials or under greenhouse conditions in order to optimize the selection for more resistant cultivars.

Transnational Nordic-Baltic collaboration

For sustainable wheat cultivation in the region, wheat cultivars with tolerance to low-temperature, freezing and drought stress, improved NUE, WUE and improved resistance to pathogens are necessary. These new cultivars should also have stable and high yields and be adapted to the environmental conditions of the Baltic Sea region. Such cultivars in combination with efficient agronomic practices can significantly reduce the impact of wheat cultivation on the environment. However, developing such cultivars requires transnational collaboration among researchers, breeders, farmers and policymakers. A network focused on wheat breeding was established recently with stakeholders from the Baltic Sea region countries to address the issues on the sustainable cultivation of wheat in the region (BalticWheat Network 2017). The network aims to identify strategies to develop wheat cultivars for sustainable agriculture, involving transnational collaboration with academia and industry and utilizing existing resources and modern breeding techniques.

Collaboration on genetic resources

Pre-breeding activities can significantly benefit from transnational collaboration. Plant genetic resources hold the key for adaptation of plants to climate change and new disease pressures (Moose and Mumm 2008). Gene banks in the Baltic Sea region have ex situ collections that can be used in pre-breeding and for crop improvement (Ingver et al. 2016). Local and exotic landraces, crop wild relatives, and re-synthesized wheat can be deployed in pre-breeding efforts, whereas advanced breeding lines and cultivars can be used directly for crop improvement.

In addition, breeding lines from regional breeding enterprises, and available cultivars in the market can also be evaluated. The European Cooperative Programme for Plant Genetic Resources (ECPGR) is a collaborative effort among European countries to preserve, promote and utilize plant genetic resources in Europe and maintains. The Nordic Genetic Resource Centre (NordGen, Alnarp, Sweden) is a Nordic gene bank that preserves landraces and genotypes for promoting genetic diversity and sustainable use of the material. Accessions deposited at NordGen were evaluated earlier for several agronomic traits. The spring wheat accessions at NordGen were analyzed for morphological traits and diversity was observed for various traits including plant height, spike length, seed shattering, days to heading and lodging (Diederichsen et al. 2012). In another study, winter wheat accessions from NordGen displayed variation for plant height, grain yield and monomeric sugars (Bellucci et al. 2015). These studies further highlight the importance of these genotypes and the potential for their use for commercial breeding in the Baltic Sea region.

Collaboration for the use of experimental infrastructures and analytical platforms

For the evaluation of plant genetic resources, several high-throughput phenotyping greenhouse facilities are available in the Nordic region such as the Finnish National Plant Phenotyping (NaPPI) facility at the University of Helsinki, Finland and the PhenoLab at the University of Copenhagen, Denmark. These automated facilities allow assessment of plant growth rates and developmental timing in time course experiments (Pavicic et al. 2017). These experiments can also be complemented with (a)biotic challenges and other environmental treatments for assessing physiological responses in the cultivar collections. Some special screening facilities have also been established such as the semi-field facility RadiMax for screening for deep rooting genotypes (University of Copenhagen, Denmark). Some of these facilities can be the first steps for screening large numbers of genotypes for automated evaluation of early vigor, NUE, WUE, abiotic stresses, deep rooting as well as other morphological and physiological traits. For a fewer number of accessions, high-precision growth facilities in Sweden such as the Biotron and Phytotron at the Swedish University of Agricultural Sciences (SLU) can be used for characterizing them for abiotic and biotic stresses; and facilities at the Aarhus University in Denmark for biotic stresses, fungicide resistance and 3D imaging of plants. The freezing chambers at Lithuanian Research Centre for Agriculture and Forestry (LAMMC) in Lithuania can provide further evaluation of wheat genotypes for winter hardiness. A Nordic university hub called NordPlant with five Nordic universities was recently established to collaborate and share the experimental infrastructures in the Nordic region for research and education and to meet future challenges in agriculture (www.nordplant.org). Nordic plant phenotyping network (NPPN) was established with Nordic and Baltic partners to develop and share technological advancements in plant phenotyping (www.nordicphenotyping.org). The European plant phenotyping network (EPPN2020) was established to promote transnational access to phenotyping infrastructures across Europe (www.eppn2020.plant-phenotyping.eu/).

Plant phenotypes also have plasticity that causes trait variation in response to environmental conditions and agricultural management practices (Gratani 2014). To assess agronomic traits, phenotyping experiments need to be performed in field conditions (Großkinsky et al. 2015a), where proximal and aerial field phenotyping are available for example at SLU (Sweden) and Copenhagen University (Denmark). For some of the traits, DNA markers can be developed for further selection of the progeny lines by genomic selection (Desta and Ortiz 2014, Bassi et al. 2016). Integrating multi-omics techniques and physiological phenotyping can help in unraveling complex molecular mechanisms underlying quantitative traits (Großkinsky et al. 2018). The need to integrate physiological phenotyping into a holistic phenomics approach (Großkinsky et al. 2015b) assessing the underlying mechanisms is addressed by the establishment of semi-high-throughput analytical assay for the determination of activity signatures of key enzymes of carbohydrate and antioxidant metabolism (Jammer et al. 2015), phytohormone profiles (Grosskinsky et al. 2011) and online monitoring of photosystem II activity by PAM chlorophyll fluorescence (University of Copenhagen, Denmark). Various omics techniques can be used to identify candidate genes for the underlying traits (Chawade et al. 2012, Chawade et al. 2013) for developing gene specific markers (Chawade et al. 2016) or silencing the candidate genes in new genotypes with targeted mutagenesis techniques such as CRISPR/CAS9 (Kim et al. 2017).

Overall, key traits can be evaluated in hundreds of genotypes by efficiently utilizing modern facilities and advanced techniques and a fewer selected genotypes can then undergo field trials at various Baltic Sea region or be used in breeding for introgression of such traits depending on the source of the desirable traits. Taken together, the facilities that are available for the BalticWheat Network offer an opportunity to assess the plant genetic resources for selecting genotypes with key trait variation adapted to the local conditions and future climate scenarios.

Collaboration for multi-environment trials

Wheat breeding in the region is conducted at companies in Denmark (Sejet and Nordic Seed), Finland (Boreal Plant Breeding Ltd), Norway (Graminor), Sweden (Lantmännen Lantbruk) and also at institutions in Estonia (ECRI), and Lithuania (LAMMC). In Poland, conventional breeding is done mainly by the commercial breeding stations Danko, Poznań Plant Breeding, Strzelce, Smolice supported by Plant Breeding and Acclimatization Institute – National Research Institute and universities. Although many of these organizations conduct field trials in more than one country, identifying climate change hotspots with key environmental differences in different regions will help in resourceful trials and efficient selection of breeding lines. For example, yellow rust has been a major disease in Sweden and Denmark for years but only recently increased in Estonia. Drought in late spring was mainly noted in Poland and Estonia in recent years and water stress in Estonia is expected to increase by 2040 (Luo et al. 2015). Strong winters are observed in the Baltic countries while they are relatively milder in southern Sweden and Denmark (Peltonen-Sainio et al. 2015). These hotspots in different countries can be efficiently explored in field trials for selecting climate-resilient breeding lines with high yield and grain quality. Several international collaborative efforts have been initiated to tackle challenges with wheat breeding. In Europe, a transnational collaborative project Whealbi was initiated to increase the diversity of wheat cultivars in Europe (www.whealbi.eu). International wheat initiative was launched to coordinate worldwide research efforts for wheat improvement (www.wheatinitiative.org). International wheat yield potential initiative (IWYP) was launched to increase the wheat yield potential by 50% in the next two decades (www.iwyp.org). Lessons learned from these international initiatives will aid defining collaborative tasks for improving wheat cultivars for the Baltic region.

Organic farming based on low input cultivars or agricultural techniques can reduce the eutrophication of the Baltic Sea (Granstedt 2012). Wide adaptation of organic farming methods would further reduce the spread of chemicals on farmland, benefit biodiversity and stimulate social and economic development in rural areas in the Baltic Sea region (Granstedt 2012). Lantmännen in Sweden has a small breeding program specifically for organic farming as the program incorporates common bunt (*Tilletia tritici* Bjerk.) and dwarf bunt (*Tilletia controversa* Kühn) resistance. NordGen has tested a subset of their wheat collection for host plant resistance to common bunt in collaboration with organic breeders. For organic production, *Tilletia* resistance is important as it is the only means of controlling the seed transmitted fungi when there is no chemical seed treatment available. Organic wheat trials are also carried out at ECRI, Estonia since 2005. A few promising breeding lines have been included in the Estonian trials and recommendations for suitability to cultivate in organic conditions are included in the characteristics of new cultivars. The material tested in local organic trials can be tested further for multi-environment trials and evaluation in the neighboring countries. In spite of the ongoing efforts aimed at breeding cultivars for organic production, the majority of Value for Cultivation or Use tests (VCU) are done in conventional conditions with limited nitrogen and fungicide applications. Very often, organic production of wheat is based on old cultivars, most of which are cultivated in parallel with cultivars developed by conventional crossbreeding programs. Hence, the establishment of a network of field trials for organic farming can motivate breeders to test their breeding material.

Joining forces to create synergism for a holistic, multidimensional pre-breeding research: taking omics to the fields

The improvement of wheat cultivars for the Baltic region in terms of, for instance, enhanced NUE will target plant processes at the molecular and individual plant scales, while the intended effects from cultivar improvement include the reduced eutrophication in the Baltic Sea area and therefore relate to the landscape and regional scales. Research is required to link these different scales, which can be achieved by investigating key physiological processes at the molecular level (e.g. in high-throughput phenotyping facilities), and assessing the effects of plant physiological modifications on the NUE of field-grown plants and crops at higher scales (Weih et al. 2017). For example, the environmental impact of improved N uptake in barley cultivars through plant breeding was assessed in a Swedish scenario study (Tidåker et al. 2016). Similar research should be performed for assessing the environmental consequences of NUE-improved wheat cultivars on nutrient inputs into surface waters of the Baltic Sea region.

Working across disciplines and environments is necessary to describe, understand and predict how to grow wheat in the changing climate. It is important to define the research priorities ('hotspots') in the Baltic Sea region. Not only the classical agronomic considerations (grain yield potential, length of growing period, lodging resistance), and quality aspects (protein and gluten contents in the grain) are of interest in cultivar selection by farmers but in the future also production characteristics (end-use grain quality) and the demands within climate change scenarios (grain yield and quality stability) will need to be increasingly considered. The success of collaboration depends on the engagement of researchers and stakeholders in the region. They should gain a better understanding of cultivar × environment × management system interactions to identify genotypes better adapted to the Baltic Sea countries through multi-environment field trials and shared use of special infrastructures and analytical platforms and expertise.

Conclusions and future perspectives

Obtaining high yields while reducing the impact of wheat production on the environment requires increasing the genetic diversity of cultivated wheat in the region and applying modern breeding techniques for selection. Participatory breeding approaches utilizing environmental hotspots and climate change scenarios will facilitate selection of breeding lines adapted to the local environment and the changing climate. Precision farming with improved agronomic practices, integrated pest management and supportive governmental policies are necessary to reduce the impact of agriculture on the environment. Thus, a transnational and holistic approach for pre-breeding, breeding and farming will enable the stakeholders to reach the goal of sustainable intensification of wheat production in the Baltic Sea region. The developed strategies could then serve as a model for a cross-border, multinational collaboration to solve geographically localized challenges in agriculture that affect several neighboring countries.

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